EXPERIMENTAL RESEARCH OF VELES PLANETARY ROVER PERFORMING SIMPLE CONSTRUCTION TASKS

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Abstract:
The paper is concerned with the problem of experimental research of Veles planetary rover performing simple construction tasks. The current state of the art in planetary rovers and their research in construction tasks are discussed. The Veles rover solution designed for construction tasks and experimental testbed are described. The experimental testbed included a test room with Moon regolith analogue. Experimental research concerning rover mobility and manipulation tasks were carried out. Experimental research consisted of various scenarios, including clearing an area that removes boulders and levelling the soil. The complementary scenario for the area preparation was to exchange the tools of the manipulator. In this case, the gripper and the shovel were used as end-effectors for moving objects, both structured or in the form of regolith. Results of selected experimental research are presented and discussed. Finally, directions of future works of the rover are pointed out.

Keywords: *planetary rover, mobility, construction tasks, manipulation tasks, in-situ re-source utilization, experimental research.*

1. Introduction

Extraterrestrial, hypothetical life has been fascinating to the human race for hundreds of years. This prompted humanity to start traveling to foreign planets and moons of the Solar System. As for the study of extraterrestrial life, planetary rovers play a key role.

Planetary rovers are unmanned ground vehicles (UGVs) intended to move across the surface of planets, asteroids or moons, in the area close to the landing spot. Their task is exploration and research, e.g., analysis of climate or soil samples. They can be both teleoperated and with various degrees of autonomy. For safety reasons, rovers usually have low maximum speed. In addition, higher speeds cause more slip and larger bulldozing of wheels on the soft ground [2, 20].

Historically, the first rovers were Lunokhods, which studied the surface of the Moon in the early 70s within the framework of the Soviet space program Luna. They were teleoperated vehicles operated by the crew located on Earth. Un-manned missions to Mars are very popular. The first rover, which in 1971 arrived safely on that planet, was a Soviet Prop-M, but contact with it was lost in several seconds. In 1997, NASA Mars Pathfinder lander with Sojourner rover landed successfully on Mars. In turn, since 2003 NASA Mars Exploration Rover program has been carried out, consisting of twin rovers Spirit and Opportunity. The purpose of the rovers is to explore the planet mainly for geological and climatic conditions. In assumption, the mission would determine whether there has been water on Mars and whether there have been conditions for life. It can be noticed that in subsequent missions, the rovers are getting bigger and bigger and have a larger and larger mass.

Recent solutions of rovers include the ExoMars rover by ESA [24] and Curiosity designed by NASA [23], which found pieces of evidence for the presence of liquid water on the Martian surface.

Modern rovers for planets' exploration have a high number of motors for driving and steering the wheels. Therefore, they are classified as highly overactuated vehicles. They usually are 6-wheeled with all-wheel independent drive and with at least outer wheels steered. As a result, they have good maneuverability, stability of motion and mobility on various terrain. Due to low speed of motion and small slips of wheels, they also have a good dead reckoning. [19]

When it comes to mobile robots for construction works in terrestrial conditions, there are few such solutions. Examples of commercially available robots are e.g., the HadrianX bricklaying machine [25] and the Husky A200, which is designed for autonomous logistic tasks [26]. However, many examples of solutions are in the research phase, including prototypical JA-WA technology for automatic concrete laying of composite walls [22] and mobile robots dedicated for habitable house construction by 3D printing [18]. On the other hand, rovers for construction works are currently in the concept or research phase. It is usually assumed that they work based on local resources, i.e., they implement the In-Situ Resource Utilization (ISRU) concept. These kinds of solutions are aimed primarily at building habitats.

Construction robots can carry out works related to the movement of the mobile platform, such as grading, manipulation activities, such as digging, and including the simultaneous movement of the mobile platform and manipulation, such as bricklaying. However, automated execution of this type of works by mobile robots is a very complex issue. It includes, among others, the problem of planning and controlling the movement of a mobile platform, a manipulator or both of them, localization and environment mapping, as well as identification of objects in surroundings based on machine vision.

From the point of view of implementing the movement of the rover's mobile platform on loose ground, typical for Mars or Moon, its mobility is of decisive importance. Mobility can be defined as a robot's ability to move with desired parameters of motion in defined environment conditions, with limitations of the robot itself taken into account [15].

Other properties of the rover's mobile platform, discussed in [19] and important from the point of view of construction works, are maneuverability, stability of motion and dead reckoning. The maneuverability is the robot's ability to change its direction of motion. The stability of motion is understood as robot resistance to the unevenness of the ground during its movement. Finally, the dead reckoning of a vehicle is the ability to estimate its location based on estimated speed, direction and time of travel with respect to a previous estimate [6].

The basis for research of rovers' mobility is terramechanics [2], which originator is Polish researcher M.G. Bekker, who was the main designer of the Lunar Roving Vehicle used in Apollo 15-17 missions on the Moon. The results of re-search in this area can also be found in works [1, 7, 9, 10, 12, 21].

Regarding rovers' motion control, this issue is the subject of, among others, work [9]. These kinds of solutions are based on the theory for mobile robots known, for example, from [6, 16]. For the rovers, an important additional issue is the modularity and reconfigurability, as well as their ability to function in case of partial failure. Examples of solutions in modularity and reconfigurability include NASA Athlete, SMC Rover system [11] and the modular robotic concepts for planetary surface excavators [8]. In turn, examples of works in the area of analysis of the possibility of operation of mobile robots after partial dam-age are [4], where the damage of environmental sensors is taken into account, and [17], in which the wheel failure is analyzed.

In turn, rover manipulation tasks are the subject of works [13, 5, 3]. The paper [13] concerns complex manipulation tasks, including moving the payload from the lander onto the rover, picking up the payload from the ground and approaching the ground with a shovel. The article [5] presents a whole-body Cartesian impedance controller for a planetary rover equipped with a robotic arm. The MSc thesis [3] analyses robust visual servo control and tracking for the manipulator of a planetary exploration rover, which was finally evaluated in a simulation environment.

This article was prepared in the scope of the PRO-ACT project, which concerns the problem of cooperation between several robots. It focused on multi-robot system architecture, task allocation by mutual negotiation, cooperative planning and task execution, cooperative simultaneous localization and mapping, cooperative manipulation as well as robot hardware adaptations. [14, 28]

This work concerns experimental research of a planetary rover performing construction tasks based on In-Situ Resource Utilisation (ISRU). ISRU assumes, among others, the construction task using the materials available on the moons or planets. It includes a scenario, the goal of which is to clear an area removing boulders and levelling the soil. This requires identifying the debris from the selected area that needs to be graded to achieve a levelled surface. The complementary objective for area preparation, analyzed in this paper, is to exchange tools for the manipulator end-effector. [14, 28]

This allows for implementing a wide range of tasks related to the construction of habitats.

2. Veles Planetary Rover

For experimental research purposes, the Veles planetary rover was prepared. Veles includes a highly off-road-capable mobile platform with high towing capabilities and the ability to carry a heavy payload. Veles platform is based on IBIS mobile robot by ŁUKASIEWICZ PIAP Institute, which was adopted for the PRO-ACT project purposes. The mechanical design of the rover and its implementation are shown in Fig. 1.

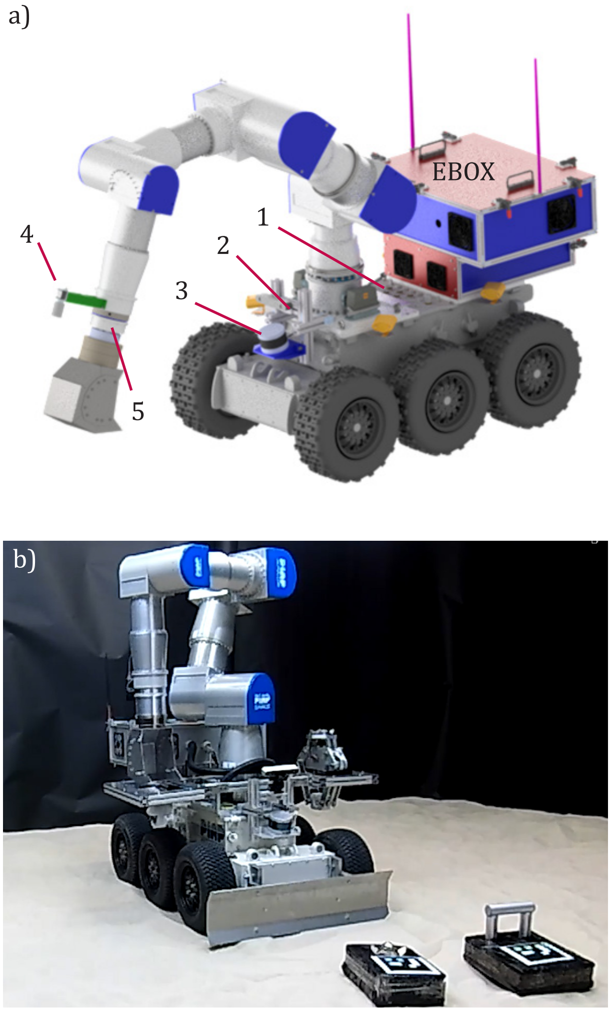


Fig. 1. Veles planetary rover: a – mechanical design, b – implementation [28]

The robot has no steered road wheels; therefore, it is more similar to the solutions used on Earth than rovers for planetary exploration. This is due to a different robot application and the assumption that it is dedicated to working in a familiar environment and performing simple construction works. It can therefore move at a higher velocity, and the supervision of its operation can be local. For this reason, it may be a simpler and therefore cheaper solution.

The Veles rover consists of a mobile platform with six non-steered and independently driven wheels, an optional grader blade mounted in front of the mobile platform, a seven DoF manipulator and a set of end-effectors including a shovel and gripper.

The so-called EBOX was placed in the rear part of the rover for powering the robotic arm, all sensors and computer subsystems (see Fig. 1a).

The EBOX houses the following electronic components:

- Board Computer (OBC),
- Motion Control CPU (MCCPU),
- Robot Arm Controller (RAC),
- Power Supply Management computer (PSU),
- Instrument Control Unit (ICU),
- Network equipment, consisting of:
  - o Network switch,
  - o Wireless router,
  - o Mesh Radio communication system,
- Ultrasonic locator device.

On the robot were also mounted sensors, including:

1. DMU30-01-0100 Inertial Measurement Unit (IMU) by Silicon Systems,
2. ZED stereoscopic camera,
3. Velodyne Puck VLP16 LiDAR,
4. Basler acA2040-25gm wrist camera,
5. Force/Torque sensor based on CL16 3F3M sensors by ZEPWN.

The locations of these sensors on the rover are illustrated in Fig. 1a using above mentioned numbers. The sensors no. 1-3 are crucial for SLAM algorithms and autonomous control. The wrist camera mounted near the gripper allows accurate pose estimation of manipulated objects. The arm is equipped with a force and torque sensor and HOTDOCK interface enabling connection with end-effectors. [28]

The HOTDOCK is a standard interface developed by Space Applications Services NV/SA (SpaceApps). The HOTDOCK is dedicated for robotic manipulation providing an androgynous coupling to transfer mechanical loads, electrical power, data and (optionally) thermal loads through a single interface. [27]

In PRO-ACT project the HOTDOCK was used, among others, to enable tool exchange of the rover's manipulator. The main benefits of the HOTDOCK include: large misalignment tolerance in translation and rotation, optimal form-fit geometry for self-guidance, embedded sensors for automatic alignment and connection status, high mechanical load capabilities, mechanical robustness of the external shape, update and integration of control and communication electronics, symmetric design for optimal robotic manipulator alignment and natural protection against dust, at least in connected mode. In Fig. 2 are shown two versions of HOTDOCK: active (a) and passive (b) as well as two Veles end-effectors: shovel (c) and gripper (d), attached to passive HOTDOCK interfaces. [28]

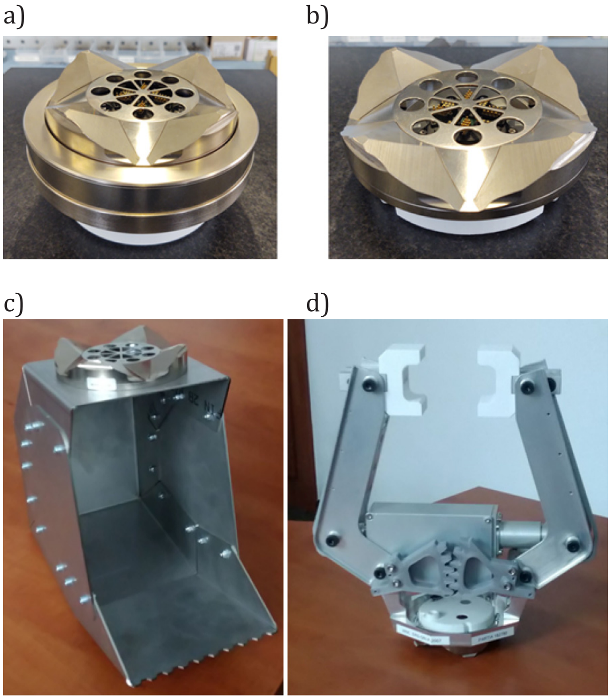


Fig. 2. Veles HOTDOCK interfaces and end-effectors:
a – active HOTDOCK, b – passive HOTDOCK,
c – shovel (left), d – gripper (right) [28]

The most important rover's parameters are:

- mass: 240 / 370 kg (without / with robotic arm and EBOX, respectively),
- maximum velocity: 5 km/h,
- maximum towing force by the robotic arm: 200 N.

In turn, gripper performance parameters are as follows:

- maximum gripping force: 475 N,
- closing/opening time: 56,5 s,
- payload maximum weight: 20 kg,
- stroke per jaw: 100 mm,
- gripper mass: 5 kg.

3. Experimental Testbed

In this work, for experimental research, the tests room with Moon regolith analogue was used.

Test room dimensions were 6 m × 6 m and about 2,5 m high. All the walls were covered with a black photographic background. The floor was divided into two sections: the work area for the test team, computers and supplementary hardware, and the test area covered with regolith analogue. The work area had dimensions of 3,5 m x 1,5 m. To simulate regolith, 3 tons of clear and dry silicon sand was used (1,5 tons of 0,1 mm to 0,5 mm grains and 1,5 tons of 0,2 mm to 0,8 mm grains). [28]

A number of supplementary mockups were prepared and used in test demonstration scenarios, as shown in Fig. 1b. Mockups were boxes covered with black foil with a marker. One of them was equipped with a simple handle, whilst the others with passive HOTDOCK. [28]

The test room shown in Fig. 3 was equipped with Marvelmind Indoor Navigation System, which is an ultrasound system for robot position estimation provided by SpaceApps. It included static beacons mounted on walls and a mobile beacon attached to Veles rover. The accuracy of the pose estimation according to manufacturer is 2 cm. Thus, this allowed an acceptable localization solution since the wheel odometry suffered a very high slip in the fine sand, and the Visual Odometry was not always reliable due to the features-poor terrain. This was because the robot's environment was too homogeneous and did not contain enough individual features to enable explicit and precise visual localization. [28]

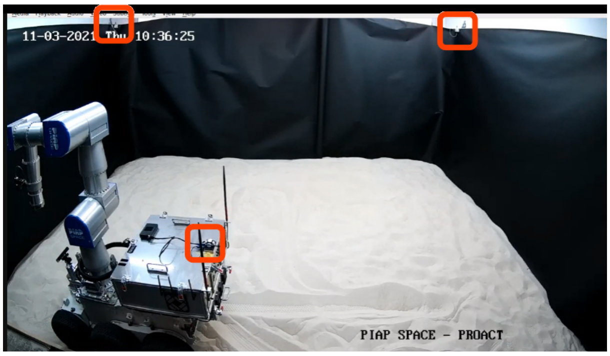


Fig. 3. Two static beacons (on walls) and a mobile beacon (on Veles rover) used within the Ultrasound Location System [28]

4. Experimental Research

This paper aims to present results of experimental research of the Veles rover performing simple construction tasks. As an example of this kind of task, among others, the scenario including tasks of grading and tool exchange was analyzed. This scenario validated two rover activities, i.e. motion of the mobile platform as well as end-effector change and manipulation capabilities. The project also investigated six other scenarios not described in this article, including cooperative mapping, cooperative unloading and assembling modules, cooperative virtual manipulation and transport, cooperative transport (with object) as well as remote gantry deployment. [28]

In this scenario, the Veles rover was equipped with a grading blade installed directly on the platform at a specific height coming from the grading tests. In addition, the end-effector interface was mounted on the manipulator tip, and the end-effector holster was prepared to carry two different end-effectors (gripper and shovel).

The whole scenario included the following steps:

1. Moving via teleoperation and setting grading blade height,
2. Digital Elevation Map generation before grading,
3. Offline determination of waypoints for Rover Guidance to follow for grading,
4. Executing grading process,
5. Post-grading Digital Elevation Map generation and repetition of grading, if necessary,
6. Moving the arm to the gripper docking pose,
7. Latching of the gripper using HOTDOCK,
8. Executing manipulation task using gripper,
9. Moving the arm to the gripper docking pose,
10. De-latching the gripper,
11. Moving the arm to the shovel docking pose,
12. Latching of the shovel using HOTDOCK.

The goal of the first task was to verify the rover ability of grading for specific grading blade height. Grading was performed in teleoperation mode, controlled by an operator, and in automatic mode, in which the rover moves based on a set of waypoints. In automatic mode, the rover guidance system got waypoints for grading and commanded the robot to reach the desired waypoints.

The example realization of the grading task is shown in Fig. 4. This task includes pose estimation and digital elevation model generation. Veles rover successfully carried out the desired task. However, grading via teleoperation was complex due to the low adhesion of regolith analogue. Sandhill visibility on records was also limited due to lightning conditions. Grading was carried out on the basis of the elevation map, determined according to LiDAR data, until the surface uniformity was obtained.

When it comes to pose estimation, it was stable, shown no drift, and correctly located the rover with respect to the map reference frame. The digital elevation model developed by SpaceApps was consistent with the rover's surroundings and was updated as the grading takes place. The elevation map representation was accurate and consistent taking into account the estimated pose and the input point clouds. [28]

Fig. 5 illustrates the digital elevation model before (left) and after (right) the grading operation.

The robotic arm movement was verified during the second part of the scenario, which covers end-effector change and manipulation capabilities. Position matched the goal within range, and the HOTDOCK was aligned to perform de-latching and latching with the gripper and shovel.

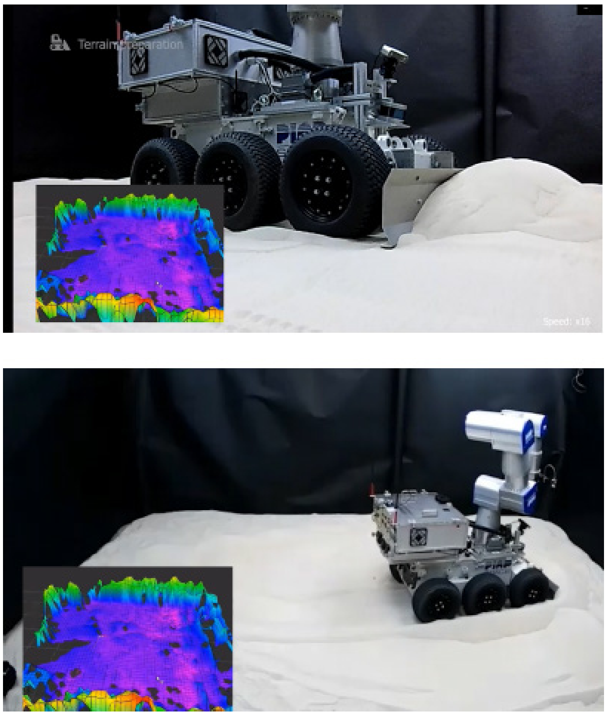


Fig. 4. Veles rover performing grading task [28]

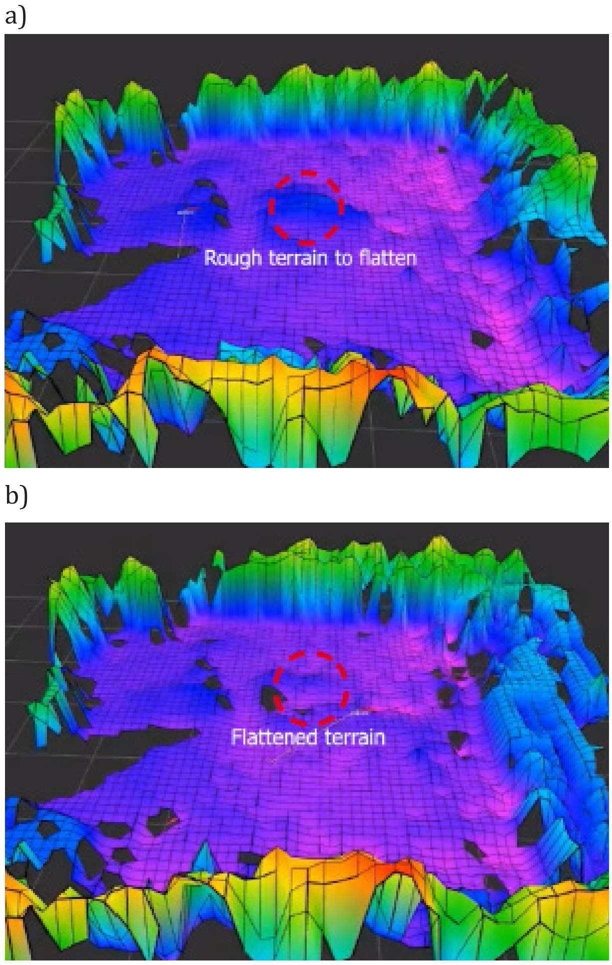
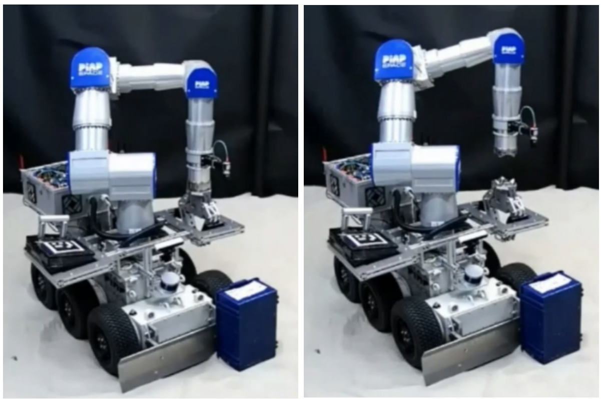


Fig. 5. Digital elevation model of the terrain before (a) and after (b) the grading operation [28]

Fig. 6 illustrates the steps taken to demonstrate the tool exchange. The sequence shows the HOTDOCK's de-latching to let go of the gripper, the arm's movement towards the second tool (shovel) and the latching of the second tool using HOTDOCK.

Video presenting PRO-ACT project concept and above-described results of experimental research are available on [29].



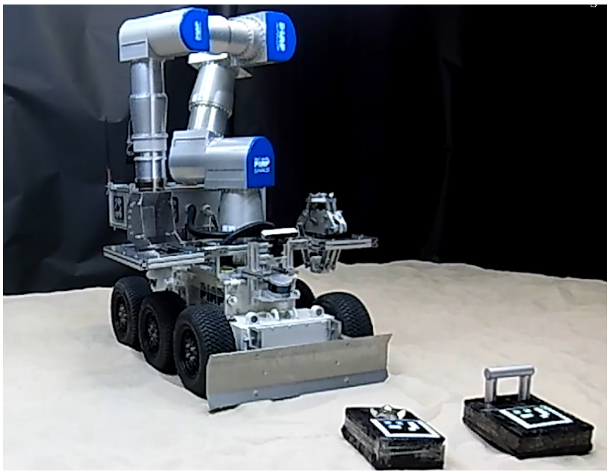


Fig. 6. Veles rover executing tool exchange task [28]

5. Conclusion

In the present work, the problem of performing simple construction tasks by planetary rover was analyzed. The rover executed two kinds of tasks: 1. grading, including motion of the mobile platform, and 2. end-effector change and manipulation using a robotic arm.

The most important conclusions of the work are summarized below.

- The robot successfully performed both grading and manipulation tasks.
- Grading via teleoperation was difficult due to the low adhesion of the regolith analogue. In this case, automation of motion control allows for stabilization of motion.
- The kinematic structure of the rover's chassis provides high stability in longitudinal movement. Still, it is characterized by large dead reckoning during turning or rotating in place.
- Thanks to a large number of degrees of freedom, the manipulator allows for the implementation of complex manipulation tasks. However, this is an overactuated solution; therefore, its automatic control is complex.

Directions of future works can cover, among others:

- Realization of cooperative manipulation and transport tasks by two robots.
- Executing other typical construction tasks like digging, rock crushing, bricklaying etc. necessary for building habitats.

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